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CALIBRATION OF RADON AND RADON PROGENY INSTRUMENTATION OF THE ACTIVE AND PASSIVE TYPE IN A LARGE RADON/THORON TEST FACILITY OF THE WALK-IN TYPE

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CALIBRATION OF RADON AND RADON PROGENY INSTRUMENTATION OF THE ACTIVE AND PASSIVE TYPE IN A LARGE RADON/THORON TEST FACILITY OF THE WALK-IN TYPE

by

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ABSTRACT

A number (45) of radon and radon progeny instruments have been calibrated in a Radon/Thoron Test Facility (RTTF) of the walk-in type. The calibration included instruments of the passive as well as the active type. Two main conditions of operation for the RTTF were chosen, namely: low aerosol concentration/low relative humidity, and high aerosol concentration/high relative humidity. The radon gas concentration was maintained essentially constant at about 45 pCi/L. The Working Level was chosen to vary from approximately 20 mWL to >350 mWL by varying the aerosol concentration and/or the relative humidity. The performance of the different instruments rated from poor to excellent depending on the type of instrument and the RTTF operating conditions. This work was requested by Atomic Energy of Canada Limited for a monitoring and remedial action program in some Elliot Lake dwellings.

Keywords: Radon; Radon progeny; Monitoring; Instrumentation; Calibration.

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ÉTALONNAGE DES INSTRUMENTS CONVENANT À LA SURVEILLANCE DU RADON ET DES PRODUITS DE FILIATION DU RADON DE TYPE RADIOACTIF ET INERTE DANS UNE GRANDE INSTALLATION EXPÉRIMENTALE, MODÈLE PLEIN-PIED, UTILISÉE À DES FINS DE SIMULATION AU COURS D'ESSAIS SUR LE RADON ET LE THORON

par

J. Bigu*

RÉSUMÉ

On a effectué l'étalonnage d'un certain nombre (45) d'instruments servant à la surveillance du radon et des produits de filiation du radon dans une grande installation expérimentale, modèle plein-pied, utilisée à des fins de simulation au cours d'essais sur le radon et le thoron (IERT). Dans le cadre de cette étude, deux types de conditions de fonctionnement ont été choisis pour l'IERT, soit à faible concentration d'aérosols/humidité relative basse et à concentration élevée d'aérosols/humidité relative élevée. La concentration du radon a été maintenue à un niveau constant d'environ 45 pCi/L. Le "Working Level" a été déterminé afin de varier entre 20 mWL environ et >350 mWL suivant les changements au niveau de la concentration d'aérosols et d'humidité relative ou de l'humidité relative. Le rendement des différents instruments s'est classé de faible à excellent selon le type d'instrument et les conditions de fonctionnement utilisés dans l'IERT. Énergie Atomique du Canada Ltée nous a demandé d'effectuer la présente étude dans le cadre d'un programme de surveillance et d'action corrective dans certaines résidences d'Elliot Lake.

Mots-clés: Radon; produit de filiation du radon; surveillance; instrument; étalonnage.

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CONTENTS

	Page
ABSTRACT	i
RÉSUMÉ	iii
INTRODUCTION	1
DESCRIPTION OF THE INSTRUMENTATION TESTED	2
EXPERIMENTAL PROCEDURE	5
EXPERIMENTAL RESULTS AND DESCUSSION	9
SUMMARY AND CONCLUSIONS	13
ACKNOWLEDGEMENTS	15
REFERENCES	15

TABLES

No.		
1.	Operating conditions of the RTTF during the instruments evaluation period	17
2.	PRIM radon gas monitors calibration data in the RTTF	18
3.	R.A.D. radon gas monitors calibration data in the RTTF	19
4.	R.A.D. radon gas monitor (new type, model E-1) calibration data in the RTTF	20
5.	Alpha-NUCLEAR calibration data in the RTTF	21
6.	CEA dosimeters calibration data in the RTTF	22
7.	CEA dosimeters calibration data in the RTTF (thoron/thoron daughter atmospheres)	23
8.	Thoron progeny data in the RTTF used in Table 7	24
9.	EDA RGA-400 and WLM-300 calibration data in the RTTF	25
10.	EDA RGA-400 andWLM-300 calibration data in the RTTF	26
11.	ORF samplers (RAD M-1) calibration data obtained in the RTTF.	27
12.	Ministry of Labour calibration data for Working Level monitors in the RTTF	28
13.	Ministry of Labour calibration data for Working Level monitors MOD-225 in the RTTF	29

INTRODUCTION

It is generally recognized that inhalation of radon progeny results in the largest single contribution to the average effective dose equivalent received by members of the public (1). Monitoring of radon progeny is, therefore, of utmost importance in order to assess potential radiation health hazards associated with occupational workers and the general public alike.

The accuracy with which radon and its progeny can be measured depends to a great extent on the type of instrument, and technique and method used. Hence, calibration of radiation instrumentation in reference radioactivity atmospheres cannot be emphasized enough.

Radon and its progeny can be measured by means of a variety of commercially available instruments of the passive and active type, using techniques which range from grab-sampling to time-integrating and continuous monitoring, employing a variety of radioactivity counting methods.

This report presents data on a technical evaluation and calibration of several radon and radon progeny instruments of the passive and active type. It includes results on two personal dosimeters of the active type, two radon gas monitors of the passive type, and several radon progeny environmental monitors (e.g., Working Level monitors) of the active type.

The evaluation of the above instrumentation was conducted in a Radon/Thoron Test Facility (RTTF) of the walk-in type (2). Tests were preferentially conducted in radon/radon progeny atmospheres, although some instrumentation was also tested in thoron/thoron progeny atmospheres.

The evaluation of the instrumentation subject of this report was requested by Atomic Energy of Canada Limited (AECL) for a monitoring and remedial action program in some Elliot Lake dwellings (3). A technical evaluation of other instrumentation used for the same purpose has been

published elsewhere (4,5).

Instrumentation for the monitoring and remedial action program was sent to the Elliot Lake Laboratory (CANMET, Energy, Mines and Resources Canada) by several organizations, such as Atomic Energy Control Board (AECB), Radiological Protection Bureau (RPB, National Health and Welfare), the Ontario Ministry of Labour (MOL), and AECL. In addition, instrumentation from the Ontario Research Foundation (ORF), R.A.D. Services (Toronto), the Canadian Institute for Radiation Safety (CAIRS), and the Elliot Lake Laboratory were also concurrently evaluated.

The data presented here were obtained during the period June-September 1985. Data collected on an earlier technical evaluation, using other types of instrumentation during March 1985, will be reported elsewhere.

DESCRIPTION OF THE INSTRUMENTATION TESTED

The instruments tested have been described in the literature. For this reason only brief comments on their operating procedure will be indicated. For simplicity, the instrumentation will be divided into three categories, namely: personal dosimeters for radon progeny; Working Level monitors; and radon gas monitors.

A. RADON GAS MONITORS

Two different radon gas monitors of the passive type were evaluated:

a) The PRIM, a passive radon gas monitor that uses thermoluminescent chips (TLD) as α-particle detectors. Radon progeny from air is removed by means of polyurethane 'foam' before entering the 'sensitive volume' of the instrument. The collection efficiency of the radon progeny formed by decay of the freshly filtered radon in the sensitive volume is electrostatically enhanced. The sensitive volume consists of an electrostatically charged metal mesh cylinder at a positive electrical

potential (1200 V) relative to a Mylar sheet covering the TLD chips. The latter are mounted on the bottom side of the upper base of the electrostatic collector. The instrument is commercially available from EDA Instruments (Toronto) under the commercial name RDT-322.

b) The R.A.D. E-1, is a radon gas monitor of the passive type that uses electrostatic enhancement similar to that of the PRIM. The R.A.D. E-1 uses CR-39 track-etch material as a detector and the radon progeny is filtered out by means of polyethylene membrane mounted on a conically-shaped electrostatic collector. The operation is similar to that of the PRIM, except for the detection system. In addition, the weight and size of the R.A.D. E-1 is substantially less than that of the PRIM.

B. PERSONAL DOSIMETERS

Two different radon progeny dosimeters of the active type were evaluated, namely the alpha-NUCLEAR and the CEA track-etch dosimeters:

a) The alpha-NUCLEAR personal dosimeter uses a diffused-junction silicon detector, and associated electronic circuitry. Sampling flow-rate is ~0.1 L/min. The dosimeter is programmable by means of a personal computer and an interface unit. The latter is mounted on the side of the dosimeter. This dosimeter provides the user with time-profile Working Level (WL), average WL and a variety of other useful data. The dosimeters can be mounted on a NiCd battery or a miner's cap lamp battery for ease of operation. This dosimeter is commercially available from alpha-NUCLEAR (Toronto) under the commercial name alpha-PRISM. Different software packages are available for different applications.

b) The CEA personal dosimeter uses a track-etch material (LR-115) as detector. Sampling flowrate is about the same as the alpha-NUCLEAR dosimeter. The CEA dosimeter has three collimators looking at three different regions of the track-etch detector covered with different

thicknesses of an absorber (polycarbonate) in order to detect ^{218}Po (RaC) and ^{212}Bi (ThC), both radioisotopes having about the same energy ~6.0 MeV, ^{214}Po (RaC')with an energy of 7.69 MeV, and ^{212}Po with an energy of 8.95 MeV. Nuclear tracks are rendered visible (under a microscope or other amplifying optical system) by chemical etching.

C. WORKING LEVEL (RADON PROGENY) MONITORS

Four different radon progeny monitors of the active type were tested:

a) The WLM-300 is manufactured by EDA Instruments (Toronto). This Working Level monitor uses a silicon-barrier detector and operates on α-particle time-integrating principles. The WLM-300 is designed to operate as a continuous monitor at a flow-rate of 1 L/min. The monitor provides total α-count, differential α-count, average Working Level, and average Working Level over any period of time. Counting times can be chosen as 6 min or 60 min. The interested reader should consult reference (6) for more detailed information regarding this instrument;

b) The RGA-400 is also manufactured by EDA Instruments, and is an outgrowth of the WLM-300. The RGA-400 consists of a radon progeny monitor and a radon gas monitor packed in a single instrument. It uses silicon-barrier detectors as α-particle detectors with their associated electronic circuitries. The RGA-400 has α-spectrometric capabilities. The two detection systems are designed to operate in series, i.e., air passes through a filter facing a silicon-barrier detector where the radon progeny is counted. The exhaust from the radon progeny sampling head/detection system is then directed to an electrostatically enhanced detection system consisting of a 3 L cylinder with a silicon-barrier detector, located at the exhaust side of the chamber, where radon gas is counted. The instrument is fully programmable and operates at a flow-rate of 1 L/min. The interested reader should consult reference (7) for more details.

c) The radon progeny monitors M-1 are manufactured by R.A.D. Services (Toronto) and are used by O.R.F. for monitoring purposes in dwellings. The monitors consist of a pump of the aquarium type (1-2 L/min), and a sampling head that uses a track-etch material (CR-39) as radon progeny detector (8). The CR-39 detector faces the sampling filter as is the common practice in radon progeny monitors.

d) The M.O.L. radon progeny monitors are similar in construction to the M-1 by R.A.D. Services, but use cellulose nitrate (LR-115 type 2) as the α-particle detector.

e) The MOD-225 is a continuous radon progeny monitor that uses TLD chips as α-particle detectors. As is standard practice, when using TLD chips for α-particle detection, a shielded and an unshielded TLD chip are used in the same sampling head. The unshielded TLD chip responds to α-, β- and γ-radiation. Hence, if the responses from the two chips are subtracted from one another, the net α-particle contribution can be estimated. Sampling flow-rate is adjustable, but usually is factory set at about 2 L/min. The MOD-225 can use LiF, CaF_2:Dy or any other TLD material. In the present case LiF chips were employed.

EXPERIMENTAL PROCEDURE

Testing and calibration of instrumentation were conducted in a Radon/Thoron Test Facility of the walk-in type (2). The instruments were tested under laboratory-controlled environmental conditions of temperature, relative humidity, aerosol concentration and radiation level (radon gas concentration and radon progeny concentration).

Tests were conducted during the period June-Sept. 1985. The operating conditions of the RTTF during this period are shown in Table 1. Two main operating conditions were selected, namely: low aerosol concentration

($\leq 1.0 \times 10^3$ cm^{-3})/low relative humidity ($\sim$40%), and high aerosol concentration ($\geq 6.0 \times 10^4$ cm^{-3})/high relative humidity ($\geq$80%).

The two 'extreme' operating conditions indicated above were intended in order to study plate-out effects in sampling heads of radon progeny monitors operating on active principles. Plate-out effects are known to occur preferentially at low aerosol concentrations, thereby leading to substantial errors in the estimation of the Working Level, WL. This effect is highly dependent on the mechanical design (geometry) of the sampling head. The case of low aerosol concentration is important in dwellings of non-smokers in cold countries where low relative humidity and low aerosol concentration compound plate-out phenomena.

High relative humidity/high aerosol concentration conditions are important to measure the effect of filter 'loading' in radon daughter instruments of the active kind. Filter loading leads to a decrease in the detector/sampling head counting efficiency, and hence, to an underestimation of WL. For instruments that use α-spectrometry principles, filter loading results in a broadening of the spectrum and a shift of the photopeaks to lower energies. These effects are caused by α-particle absorption and self-absorption effects in the filter material, partially caused by the deposition of aerosol and water vapour in the filter. The case of high aerosol concentration/high relative humidity is quite relevant in underground uranium mines where the above conditions prevail and can lead to large errors in the estimation of WL. Furthermore, the presence of high concentrations of corrosive aerosols and water vapour is known to affect the performance of electronic circuitry of radiation instruments.

Relative humidity and aerosol concentrations do not affect radon gas concentrations in the RTTF. However, air moisture content may affect the response of radon gas monitors operating on electrostatic collection

principles.

Experiments were conducted within a quite narrow range of values for the radon gas concentration ~45 pCi/L ± 5 pCi/L. Working Levels ranged from about 20 mWL to >350 mWL. The Working Level was changed by changing the aerosol concentration and/or varying the relative humidity in the RTTF.

Radon gas concentrations were maintained constant, within less than ±10%, for extended periods, i.e., up to three months. The Working Level was maintained constant, within about ±10%, for periods of 8 h to 24 h, depending on the test conducted. Rapid variations in WL were also introduced, whenever necessary, to investigate the response and performance of some instruments to transient conditions.

Radon/radon progeny atmospheres were produced by injecting radon gas, ^{222}Rn, into the RTTF by means of radon gas flow-through sources model Rn-1025 manufactured by Pylon Electronics Development (Ottawa).

Aerosol was generated using an atomizer model 3076 in conjunction with its associated air supply system, column desiccator, and electrical charge neutralizer, all manufactured by T.S.I (U.S.A). An aqueous solution of NaCl (0.001 - 1 g/L) was used to produce the aerosol cloud. Relative humidity was varied by means of conventional humidifiers.

Radon and aerosol were injected into the RTTF through injection ports located opposite the air exhaust system.

Radon gas concentration in the RTTF was continuously monitored by means of two radon gas continuous monitoring systems, namely: the RGM-2, a radon gas monitor manufactured by Eberline (U.S.A), and a radon gas monitoring system developed in-house, the RM-1003/AIM-65 system (RM-1003, for short). The RGM-2 and RM-1003 systems provided radon concentration [^{222}Rn], measurements every hour and 20 min, respectively. In addition, radon gas concentrations were periodically measured by grab-sampling, using the

scintillation cell method, and by the two-filter method (9,10).

Radon daughter concentrations were measured by grab-sampling using the Thomas-Tsivoglou method, and the Kusnetz method (11,12). Radon daughter concentrations and WL by grab-sampling were measured every 40 min. A calibrated Working Level monitor, model WLM-300, manufactured by EDA, was also used to record the WL continuously, i.e., one measurement every hour.

Radon gas and radon daughter measurements were conducted at at least two different locations simultaneously in an area where radiation instruments to be calibrated were located. Results from different locations were taken and an average was calculated in each case.

Air temperature, relative humidity and barometric pressure were measured using a meteorological package manufactured by alpha-NUCLEAR (Toronto) consisting of a data logger model 650 in conjunction with air temperature, dew point and barometric pressure probes, models 602, DS 001, and 604, respectively. Aerosol concentration was measured by drawing air samples continuously through two condensation nuclei counters models, namely model Rich 200, manufactured by Environment One (U.S.A), and model 3020, manufactured by TSI (U.S.A).

Radiation instruments to be calibrated were placed in a large three-shelf metal mesh structure so designed as to produce minimum disturbance to the air flow in the RTTF. Several instruments were placed on each shelf. However, special care was taken to minimize mutual instrument interference or disturbance or air patterns by the instruments.

The readings of the instruments were compared with radon gas concentration and/or Working Level measurements carried out by the standard (calibrated) instrumentation used for monitoring purposes.

A variety of instruments were tested at different environmental conditions of relative humidity, aerosol concentration and radioactivity

levels. Radon and radon daughter monitors, and radon daughter dosimeters, of the active and passive type were tested. The instruments operated on a continuous, or quasi-continuous, i.e., intermittent, fashion using either time-integrating techniques, followed by differential counting, or total α-count. Some instruments operated continuously, whereas others were meant to operate for an 8-hour period at a time. The radiation detection system of the instruments used ranged from electronic detectors, such as silicon-barrier (SiB), and diffused-junction (DJ) detectors, to thermoluminescent detectors (TLD), track-etch film detectors, and scintillation cells, with and without electrostatic collection enhancement. Forty-five instruments were tested and calibrated.

EXPERIMENTAL RESULTS AND DISCUSSION

The operating conditions of the RTTF are shown in Tables 1 and 8. The Tables show that the range of values for the different variables of interest was as follows:

a) Temperature (T): 24-30^{o}C

b) Relative humidity (RH): 31-85%

c) Aerosol concentration (N): 0.4×10^{3} - 8×10^{4} cm^{-3}

d) Radon daughter Working Level (WL): ~20-360 mWL

e) Thoron daughter Working Level WL(Tn): 1.2-7.8 WL

f) Radon gas concentration [^{222}Rn]: ~45 pCi/L $\pm$ 10%

g) Equilibrium factor (F): 0.05-0.66

h) [^{214}Pb]/[^{218}Po]: 0.07-0.95

i) [^{214}Bi]/[^{218}Po]: 0.04-0.80

j) [^{212}Bi]/[^{212}Pb]: 0.48-0.54.

As indicated previously two main RTTF operating conditions were chosen for the instrumentation evaluation, namely: low aerosol concentration/low

relative humidity, and high aerosol concentration/high relative humidity. The former conditions resulted in low WL, WL(Tn), progeny concentrations, radon progeny disequilibrium ratios, DR, (items h and i), and low equilibrium factors (F). The opposite was true for high aerosol concentration/high relative humidity conditions. It should be noted that the square brackets are used here to denote concentration.

The results of the instrument evaluations are given in Tables 2 to 7, and Tables 9 to 13.

Table 2 shows data obtained with four PRIMS. Two units used CaF_2:Dy as TLD material, whereas the other two used LiF. The sensitivity of the PRIMS using CaF_2:Dy was substantially higher than that of the PRIMS using LiF. In all cases, the radon gas monitors significantly underestimated the radon gas concentration. PRIMS No. 2526 and 2634 were located on the top shelf of the metal mesh cabinet, whereas No. 2508 and 2627 were located on the bottom shelf. This geometrical arrangement of the monitors played no role in their response to radon gas, as concentration was quite uniform over this region. The calibration factor, CF, is indicated by the column PRIM/$[^{222}Rn]_{RTTF}$ (=CF) from which the true $[^{222}Rn]$ can be calculated.

Table 3 shows data corresponding to 12 radon gas monitors using passive diffusion and electrostatic collection enhancement, and CR39 as a detector, i.e., the R.A.D. E-1 radon monitors. The radon gas concentration measured by these monitors is indicated in the table by $[^{222}Rn]_{obs}$. The monitors were located on the three shelves of the metal mesh cabinet, four units on each shelf. The response of individual units differed substantially from one another. The average calibration factor obtained from the 12 units was $[^{222}Rn]_{obs}/[^{222}Rn]_{RTTF} = 0.61 \pm 0.34$. In general, all the units underestimated the radon gas concentration. One unit (No. 9) failed to produce any result because of electronic circuitry malfunction.

Table 4 shows three tests performed on a modified R.A.D. E-1 monitor. The monitor is an improved version of the ones shown in Table 3. The results with this modified monitor were significantly better giving a calibration factor of 0.92 ± 0.33.

Table 5 shows data obtained with three alpha-NUCLEAR dosimeters. The results obtained can be divided into the period June 18 to June 28, 1985, i.e., low N/low RH, and the period July 15 to July 26, 1985, i.e., high N/high RH. The calibration factors for these two periods were, respectively: $\overline{WL}_{DOS}/\overline{WL} = 0.67 \pm 0.12$, and $\overline{WL}_{DOS}/\overline{WL} = 0.96 \pm 0.08$. The bars over the symbol WL are used to indicate average (mean) values. The symbol DOS is used to indicate dosimeter.

The calibration factors calculated for the alpha-NUCLEAR dosimeters indicate that the dosimeters significantly underestimated WL under conditions of low aerosol concentration (N) and low relative humidity (RH) due most probably to plate-out on the sampling head. Under conditions of high aerosol concentration and high relative humidity, the response of the instrument can be rated as excellent, i.e., $CF = 0.96 \pm 0.08$.

Table 6 shows data pertaining to ten track-etch dosimeters designed by C.E.A. The average calibration factor obtained for the ten dosimeters was $\overline{CEA}/\overline{WLM} = CF = 1.01 \pm 0.09$. Data from the C.E.A. dosimeter are given in Working Level Month (WLM). The results obtained with this dosimeter for radon progeny can be rated as excellent.

Table 7 shows data for six CEA dosimeters exposed to a thoron/thoron progeny atmosphere (see Table 8). The results for the thoron progeny are only fair, i.e., the dosimeters underestimated WL(Tn) by more than 20%, i.e., $CF = 0.77$.

Table 9 gives data for four radon progeny continuous monitoring systems manufactured by EDA Instruments, i.e., two WLM-300's (WLM for short), and two

RGA-400's (RGA for short). The calibration factors obtained were ~0.79 ± 0.08 for the RGAs, and ~0.9 ± 0.08 for the WLMs. The operating conditions for the RTTF during this period were, in general, low N/low RH. Hence, some plate-out is suggested. The lower CF values for the RGAs were most probably due to spectrum overlapping as these instruments have α-spectrometry capabilities (7). It should be noted that the RGA and WLM sampling heads are identical. The performance of the RGAs can be rated as fair, whereas that of the WLM was good under the experimental conditions of the test.

Table 10 shows the performance of the same instruments as before (Table 9), but under conditions of high aerosol concentration and high relative humidity. The performance of the instruments was significantly better under these environmental conditions. The occasional low values for CF shown in Table 10, are due to filter clogging under sustained exposure to high aerosol concentration and high air water vapour content. For those cases where little or no filter clogging occurred, i.e., RGA No. 006 and WLM No. 064, the calibration factors were, respectively, 0.92 ± 0.08 and 0.98 ± 0.09, which can be rated from quite good to excellent.

Table 11 gives data pertaining to six R.A.D. M-1 radon progeny monitors used by ORF. The results show that the average CF(= $\overline{ORF}/\overline{WL}$) obtained for these instruments was quite high, i.e., CF = 1.37 ± 0.33. In other words, the instruments, on the average, overestimated WL. Table 11 shows that the performance of the instruments was better at high Working Levels, i.e., high N/high RH, than at low Working Levels.

Table 12 shows data corresponding to three radon progeny monitors used by MOL which were similar to those used by ORF. These monitors slightly overestimated the Working Level. The average calibration factor obtained for the three units was $\overline{CF}$ = 1.16 ± 0.04.

Table 13 presents the results obtained with two radon progeny monitors,

model MOD 225. The average calibration factor for these two units was: $\overline{CF}$ = 1.03, which can be considered fairly good.

SUMMARY AND CONCLUSIONS

The radon gas monitors, i.e., PRIM and RAD E-1, did not perform satisfactorily. They significantly underestimated [^{222}Rn]. It should be noted that both types of instrument operate on electrostatic principles which are highly dependent on air moisture content. However, the RAD E-1 should not be adversely affected by air moisture as the instrument uses polyethylene as a passive diffusion barrier. Polyethylene is quite an effective water vapour barrier. It was found that the new RAD E-1 prototype performed substantially better than the older prototype. However, this comparison is based on the performance of only one unit, whereas the performance of the old type is based on twelve units.

The performance of the alpha-NUCLEAR dosimeters was rather poor under conditions of low aerosol concentration and low relative humidity. Under these conditions, the dosimeters appreciably underestimated WL most probably due to radon progeny plate-out in the sampling heads. However, at high aerosol concentration and high relative humidity, the performance of the dosimeters was excellent.

The CEA track-etch dosimeters performed very well under all experimental conditions. However, when the dosimeters were exposed to thoron/thoron progeny atmospheres, the dosimeters underestimated WL(Tn) by more than 20%. It should be noted that no other instrumentation in these series of calibrations was tested with thoron/thoron progeny atmospheres.

The performance of the RGA-400 and WLM-300 monitors was fair (RGA-400) to good (WLM-300) under low aerosol concentration and low relative humidity. They all underestimated WL. The performance of the instruments improved

sensibly under conditions of high aerosol concentration and high relative humidity, i.e., from quite good (RGA-400) to excellent (WLM-300). Occasional filter clogging occurred, however, under sustained high aerosol concentration exposure. This effect has also been observed for other instruments tested during the same period but reported elsewhere (4).

The track-etch radon progeny monitors used by ORF and MOL all overestimated WL by ~15% (MOL) to ~35% (ORF). The radon progeny monitors MOD 225 operated quite satisfactorily in this test.

It should be emphasized that while all instruments using electronic solid-state detectors, e.g., RGA-400, WLM-300 and alpha-NUCLEAR dosimeters, provided a direct reading of the radiation level; instrumentation using TLD and track-etch detectors did not. In the latter case, TLD and track-etch data were obtained in other laboratories, e.g., AECB, RPB, CAIRS and RAD Services, and sent to the Elliot Lake Laboratory for comparison with RTTF radiation exposure data for calibration purposes.

Some of the discrepancies found between RTTF radiation exposure data and instrumentation data were caused by:

a) α-particle self-absorption in aerosol, dust and filter material;

b) filter clogging because of excessive dust, aerosol and water vapour deposition on the sampling filter;

c) plate-out of radon and thoron progeny in sampling heads;

d) improper conversion factors, including α-count efficiency factors, programmed in some instruments, e.g., RGA-400, etc.;

e) lack of sampling flow-rate constancy, mainly because of the use of free-running sampling pumps. Servo-controlled sampling pump systems eliminate this problem altogether.

The overall performance of the instrumentation tested here can only be considered fair. More improvement is necessary in some instruments for

adequate reliability. Calibration tests of the nature reported here should be conducted frequently, at least twice a year.

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REFERENCES

1. United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), 1982. Ionising Radiation: Sources and Biological Effects. 1982 Report to the General Assembly, United Nations, New York (1982).

2. Bigu, J., "A walk-in radon/thoron test facility"; Am Ind Hyg Assoc J, vol 45, No. 8, pp 525-532, 1984.

3. Bigu, J., "Effect of several radiation control measures for remedial purposes in a dwelling in the Elliot Lake area", Division Report M&ET/MRL 86-66(TR), CANMET, Energy, Mines and Resources Canada; 1986.

4. Bigu, J., "Calibration of the Pylon AB-5/AEP system, a continuous radon daughter Working Level monitor"; Division Report M&ET/MRL 86-64(TR), CANMET, Energy, Mines and Resources Canada; 1986.

5. Bigu, J., "Calibration of the Pylon AB-5/EL and AB-5/PRD systems, two continuous radon gas monitors"; Division Report M&ET/MRL 86-65(TR), CANMET, Energy, Mines and Resources Canada; 1986.

6. Bigu, J. and Kaldenbach, R., "Theory, operation and performance of a time-integrating, continuous, radon (thoron) daughter Working Level monitor";

Radiat Prot Dosim, vol. 9, pp 19-26; 1984.

7. Bigu, J. and Kaldenbach, R., "A microprocessor-based continuous monitor with alpha-spectroscopy capabilities for the determination of radon, thoron and their progeny"; Radiat Prot Dosim, vol. 12, pp 251-260; 1985.

8. Pai, H.L., "Automatic discrimination and read-out of tracks of RaA and RaC' on CR-39 using image analysis"; Proc of Occup Radiation Safety in Mining, pp. 480-482; H. Stocker (Ed.), Canadian Nuclear Association, Toronto, 1985.

9. Thomas, J.W. and LeClare, P.C., "A study of the two filter method for radon-222"; Health Physics, vol. 18, pp 113-122, 1970.

10. Mayya, Y.S. and Kotrappa, P., "Modified double filter method for the measurement of radon or thoron in air"; Ann Occup Hyg, vol 21, pp 169-176, 1978.

11. Thomas, J.W., "Measurements of radon daughters in air"; Health Physics, vol. 23, pp 783-789, 1972.

12. Kusnetz, H.L., "Radon daughters in mine atmospheres"; Ann Ind Hyg Assoc J, vol. 17, p. 1, 1956, (see also Ind Hyg Assoc Quarterly, March 1956).

Table 1 - Operating conditions of the RTTF during the instruments evaluation period*

Date	[^{222}Rn] RM-1003 pCi/L	[^{222}Rn] RGM-2 pCi/L	$\overline{WL}$ mWL	T °C	RH %	N cm^{-3}	DR	WL mWL	F	Remarks
June 18/85	49.1±4.8	41.9	40.5±5.1	26.0	40.0	~$1.0x10^3$	1:0.15:0.05	39	0.09	
				-	-	-	1:0.28:0.26	50		
June 19	48.9±3.4	41.6	31.8±1.9	24.4	36.5	~$0.4x10^3$	1:0.1:0.1	31	0.07	
				26.0	39.0	-	1:0.18:0.08	37		
June 20	46.9±6.5	41.4	33.5±2.4	25.0	36.4	$0.42x10^3$	1:0:12:0.1	32	0.08	
				-	-	$0.65x10^3$	1:0.21:0.14	39		
June 21	49.4±9.4	42.4	41.8±4.4	25.0	34.9	$0.65x10^3$	1:0.17:0.15	38	0.09	
				-	-	$1.0x10^3$	1:0.25:0.18	53		
June 23	48.5±5.5	42.2	-	26.0	45.5	$0.65x10^3$	-	-	-	
				-	-	$1.20x10^3$	-	-		
June 24	47.9±4.4	40.0	21.5±1.1	24.6	33.1	$0.28x10^3$	1:0.08:0.07	21	0.05	
				26.0	33.4	$0.38x10^3$	1:0.14:0.04	25		
June 25	47.2±5.5	40.9	25.4±2.6	24.9	32.6	$0.65x10^3$	1:0.07:0.09	24	0.06	
				27.3	32.8	$1.25x10^3$	1:0.17:0.02	31		
June 26	47.9±6.4	41.1	31.6±2.4	26.0	31.0	$0.8x10^3$	1:0.1:0.08	29	0.07	
				30.1	31.5	$3.0x10^3$	1:0.21:0.1	36		
June 27	52.5±7.7	45.3	36.1±3.9	24.0	32.9	$0.65x10^3$	1:0.12:0.07	32	0.07	
				27.8	33.2	$1.5x10^3$	1:0.23:0.24	46		
June 28	50.0±7.7	42.4	43.6±5.4	24.8	35.5	$0.65x10^3$	1:0.19:0.15	37	0.09	
				28.9	36.8	$1.85x10^3$	1:0.28:0.08	56		
July 15	48.1±6.0	41.6	52.0	24.5	47.5	$0.55x10^3$	1:0.16:0.15	38	0.12	
				28.1	52.6	$2.8x10^3$	1:0.33:0.26	70		
July 16	48.0±5.3	42.2	247.5	24.8	59.7	$0.45x10^3$	1:0.14:0.04	31	0.55	Aerosol injected at 9:15
				26.6	72.9	$7.0x10^4$	1:0.7:0.47	268		
July 17	49.1±7.0	42.9	286.4	24.3	77.0	$7.2x10^4$	1:0.57:0.39	254	0.62	
				27.5	80.0	$7.6x10^4$	1:0.77:0.64	334		
July 18	48.3±6.5	42.8	285.0	24.7	80.2	$7.5x10^4$	1:0.65:0.58	253	0.63	
				25.7	82.8	$8.0x10^4$	1:0.90:0.73	333		
July 19	49.5±4.2	40.7	297.1	24.8	82.0	$2.7x10^4$	1:0.59:0.40	232	0.66	Aerosol instability
				29.0	82.9	$8.0x10^4$	1:0.95:0.71	358		
July 20	49.5±4.2	42.9	-	26.0	84.0	$1.8x10^3$	-	-	-	
July 21	50.7±4.8	43.9	-	24.0	84.5	$2.0x10^3$	-	-	-	
July 22	45.5±5.0	39.9	246.8±7.6	22.1	83.0	$2.1x10^3$	1:0.11:0.04	252	0.58	Aerosol injected at 8:45
				23.8	83.4	$7.0x10^4$	1:0.78:0.51	275		
July 23	48.9±7.3	41.8	264.4±16.0	21.4	83.9	$6.0x10^4$	1:0.56:0.43	260	0.58	
				24.7	84.3	$7.0x10^4$	1:0.82:0.60	318		
July 24	46.1±5.5	40.2	243.4±14.4	22.6	83.9	$6.8x10^4$	1:0.59:0.33	234	0.56	
				25.9	84.2	$7.0x10^4$	1:0.85:0.71	288		
July 25	47.9±5.0	40.5	244.1±11.8	24.9	85.3	$6.8x10^4$	1:0.57:0.42	238	0.55	
				25.4	85.7	$7.2x10^4$	1:0.79:0.65	280		
July 26	46.4±5.4	42.5	255.4±10.0	23.6	83.0	$6.5x10^4$	1:0.63:0.51	256	0.57	
				27.1	85.3	$7.0x10^4$	1:0.86:0.80	292		

Note: The two values for T, RH, N, DR and WL represent the minimum (top), and maximum (bottom) values measured during a regular 8 hour working day.

Table 2 - PRIM radon gas monitors calibration data in the RTTF

Date	PRIM No.	Exposure Time (h)	TLD-Reading (nC)	PRIM* (pCi/L)	$[^{222}Rn]_{RTTF}$+ (pCi/L)	$\frac{PRIM}{[^{222}Rn]_{RTTF}}$	Remarks
July 15-19/85	2508	102.2	89.3	26	45.4±4.5	0.57	TLD:CaF_2:Dy
"	2526	102.2	97.8	29	45.4±4.5	0.64	TLD:CaF_2:Dy
July 15-26/85	2627	270.1	41.4	9	45.0±4.5	0.20	TLD:LiF
"	2634	270.1	30.0	9	45.0±4.5	0.20	TLD:LiF

* The values given under the heading indicate radon gas concentrations (pCi/L) measured by the instrument (PRIM).

+ Averaged value measured in the RTTF during the period indicated.

Table 3 - R.A.D. radon gas monitors (old type model E-1) calibration data in RTTF. Exposure time: July 30/August 1, 1985 (48 h). The average radon gas concentration measured in the RTTF during this period was $[^{222}Rn]_{RTTF}$ = 49.6 pCi/L.

RAD No.	$[^{222}Rn]_{obs}$* (pCi/L)	$[^{222}Rn]_{obs}/[^{222}Rn]_{RTTF}$
9	-	-
10	37.8	0.76
13	12.0	0.24
21	37.4	0.75
30	14.4	0.29
37	21.7	0.44
39	45.6	0.92
42	61.0	1.23
43	17.3	0.35
47	29.2	0.59
49	9.8	0.20
82	49.5	1.00

* Radon gas concentration measured by the instrument at R.A.D. Instruments (Toronto).

Table 4 - R.A.D. radon gas monitor (new type, model E-1) calibration data in the RTTF.

Date	$[^{222}Rn]_{RTTF}$ (pCi/L)	$[^{222}Rn]_{RAD}$* (pCi/L)	$[^{222}Rn]_{RAD}/[^{222}Rn]_{RTTF}$	Exposure Time h
July 15-19/85	45.6	59.5	1.30	102.0
July 23-25/85	43.5	30.1	0.69	49.8
July 25-26/85	44.4	34.7	0.78	21.9
			Ave: 0.92 ± 0.33	

*Radon gas concentration measured by the instrument at R.A.D. Instruments (Toronto).

Table 5 - Alpha-NUCLEAR calibration data in the RTTF

Date	$\overline{WL}$ (mWL)	Dosimeter Number No. 9 (mWL)	No. 56 (mWL)	No. 61 (mWL)	$\overline{WL}_{DOS}$	$\overline{WL}_{DOS}/\overline{WL}$
June 18/85	40.5±5.1	27.4(25.0)	30.2(27.0)	36.2(31.0)	31.3	0.77
June 19/85	31.8±1.9	15.8(14.0)	19.4(17.0)	23.2(21.0)	19.5	0.61
June 20/85	33.5±2.4	17.9(17.0)	22.2(20.0)	28.5(27.0)	22.9	0.68
June 21/85	41.8±4.4	26.0(24.0)	33.2(30.0)	37.9(35.0)	32.4	0.77
June 24/85	21.5±1.1	7.0(6.0)	8.0(7.0)	15.4(14.0)	10.1	0.47
June 25/85	25.4±2.6	11.2(10.0)	14.6(14.0)	- *	12.9	0.51
June 26/85	31.6±2.4	18.5(16.0)	22.5(20.0)	25.7(23.0)	22.2	0.70
June 27/85	36.1±3.9	24.6(21.0)	29.4(25.0)	36.3(32.0)	30.1	0.83
June 28/85	43.6±5.4	19.7(18.0)	32.4(29.0)	39.0(36.0)	30.4	0.70
July 15/85	52.0	33.9(32.0)	40.8(38.0)	42.7(41.0)	39.1	0.75
July 16/85	247.5	206.9(159.0)	247.0(189.0)	230.9(178.0)	228.3	0.92
July 17/85	286.4	251.5(227.0)	296.3(264.0)	282.9(260.0)	276.9	0.97
July 18/85	285.0	241.7(217.0)	282.7(252.0)	273.7(247.0)	266.0	0.93
July 19/85	297.1	257.7(234.0)	309.4(274.0)	292.2(262.0)	286.4	0.96
July 22/85	246.8±7.6	214.6(169.0)	241.4(189.0)	254.4(201.0)	236.8	0.96
July 23/85	264.4±16.0	233.0(210.0)	261.9(234.0)	283.0(257.0)	259.3	0.98
July 24/85	243.4±14.4	222.1(197.0)	257.0(228.0)	257.4(233.0)	245.5	1.01
July 25/85	244.1±11.8	234.1(210.0)	275.9(246.0)	266.7(240.0)	258.9	1.06
July 26/85	255.4±10.0	238.9(214.0)	279.6(247.0)	269.7(244.0)	262.7	1.03

* No experimental data.

Notes: a) Values in brackets include readings during the growth period;
b) $\overline{WL}_{DOS}$ represents the average value of the three dosimeters; and
c) $\overline{WL}$ is the average value measured in the RTTF during the exposure period.

Table 6 - CEA dosimeters calibration data in the RTTF*

Date	WLM** (mWLM)	Dosimeter Number No. 1024 (mWLM)	No. 1025 (mWLM)	No. 1026 (mWLM)	No. 1029 (mWLM)	No. 1030 (mWLM)	$\overline{CEA}$+ (mWLM)	$\overline{CEA}/\overline{WLM}$
June 19-21/85	4.82	5.0	5.0	7.0	4.0	5.0	5.2	1.08
July 15-19/85	49.0	52.0	50.0	50.0	-	-	50.7	1.03
July 15-26/85	106.3	-	-	-	102.0	81.0	91.5	0.86
		Dosimeter Number No. 1027 (mWLM)	No. 1028 (mWLM)	No. 1031 (mWLM)	No. 1032 (mWLM)	No. 1033 (mWLM)		
June 24-28/85	7.2	7.0	9.0	9.0	7.0	8.0	8.0	1.11
July 22-25/85	37.7	-	-	41.0	38.0	36.0	38.3	1.02
July 22-26/85	57.3	55.0	56.0	-	-	-	55.5	0.97
							Average:	1.01

* Average exposure per day: 8 hours.

** Working Level Month (WLM) measured in the RTTF.

\+ Average WLM measured by the CEA dosimeters.

Table 7 - CEA dosimeters calibration data in the RTTF
(thoron/thoron Daughter atmospheres)*

Date	WLM (mWLM)	Dosimeter Numbers No. 1028 (mWLM)	No. 1029 (mWLM)	No. 1030 (mWLM)	No. 1031 (mWLM)	No. 1032 (mWLM)	No. 1033 (mWLM)	$\overline{CEA}$ (mWLM)	$\overline{CEA}/\overline{WLM}$
Sept 23-24/85	430	328	-	297	347	-	-	324	0.75
Sept 25/85	370	-	299	-	-	314	266	293	0.79

* Average exposure per day: 8 hours.

Table 8 - Thoron progeny data in the RTTF used in Table 7.

Date	$\overline{WL(Tn)}$ (WL)	$[^{212}Pb]$ (pCi/L)	$[^{212}Bi]$ (pCi/L)	$[^{212}Bi]/[^{212}Pb]$	$\overline{N}$ (cm^{-3})
Sept 23/85	7.45±0.43	57.2±3.2	30.8±2.4	0.54±0.02	$2.7x10^3$
Sept 24/85	1.22±0.38	9.4±2.8	4.8±2.4	0.48±0.09	$8.8x10^2$
Sept 25/85	7.79±4.92	60.3±38.0	28.7±19.4	0.48±0.07	$2.5x10^4$

Table 9 - EDA RGA-400 and WLM-300 calibration data in the RTTF.

Date	$\frac{\overline{\text{RGA No. 006}}}{\overline{\text{WL}}}$	$\frac{\overline{\text{RGA No. 014}}}{\overline{\text{WL}}}$	$\frac{\overline{\text{WLM No. 030}}}{\overline{\text{WL}}}$	$\frac{\overline{\text{WLM No. 064}}}{\overline{\text{WL}}}$
June 18/85	0.87	0.87	1.05	0.96
June 19/85	0.73	0.73	0.82	0.84
June 20/85	0.80	0.80	0.90	0.91
June 21/85	0.86	0.86	0.97	0.95
June 24/85	0.59	0.63	0.72	0.78
June 25/85	0.77	0.78	0.90	0.93
June 26/85	0.71	0.74	0.83	0.84
June 27/85	0.83	0.85	0.96	0.97
June 28/85	0.85	0.85	0.96	0.96
Average:	0.78±0.09	0.79±0.08	0.90±0.10	0.90±0.07

Notes: a) $\overline{\text{WL}}$ is the average value measured in the RTTF during the sampling period.

b) $\overline{\text{RGA}.....}$, and $\overline{\text{WLM}.....}$ represent the average values measured by the RGA and WLM, respectively.

Table 10 - EDA RGA-400 and WLM-300 calibration data in the RTTF

Date	RGA No. 006 $\overline{WL}$	RGA No. 014 $\overline{WL}$	WLM No. 030 $\overline{WL}$	WLM No. 064 $\overline{WL}$
July 15/85	0.88	0.88	0.98	0.97
July 16/85*	0.87	0.84	0.93	0.90
July 17/85	1.01	0.98	1.11	1.07
July 18/85	0.96	0.92	1.02	1.04
July 19/85[1]	0.95	0.84	0.71+	1.04
July 22/85[2]	0.74	0.55	0.83	0.81
July 23/85[3]	0.85	0.66	1.02	0.89
July 24/85	0.98	1.00	0.89	1.01
July 25/85	1.02	1.04	0.69	1.07
July 26/85	0.94	0.98	0.52	0.99

* Aerosol injected at 9:15.
\+ Filter clogged because of aerosol loading.
1 Aerosol off at 15:40.
2 Aerosol injected at 8:45.
3 Filters of RGA No. 006 and 014, and WLM No. 064 changed at 20:39 because of aerosol loading.

Table 11 - ORF samplers (RAD M-1) calibration data obtained in the RTTF

Date	$\overline{WL}$* (mWL)	ORF Samplers No. 26 (mWL)	No. 33 (mWL)	No. 47 (mWL)	No. 82 (mWL)	No. 57 (mWL)	No. 96 (mWL)	$\overline{ORF}$ (mWL)	$\overline{ORF}/\overline{WL}$
June 19-21/85+	35.6	50.0	70.0	-	-	-	-	60.0	1.68
June 24-28/85+	31.7	-	-	50.0	39.0			44.5	1.40
July 15-18/85[1]	209.2	-	-	-	-	210.0	220.0	215.0	1.03
								Average:	1.37±0.33

* Represents the Working Level obtained from the average of grab-sampling data (8 samples/day), and data from two calibrated continuous Working Level monitors WLM-300 (1 reading/hour).

\+ Low aerosol concentration and low relative humidity.

[1] High aerosol concentration and high relative humidity.

Note: The ORF monitors were operated for an 8-hour/day at a time.

$\overline{ORF}$ represents the average Working Level measured by the six ORF samplers.

Table 12 - Ministry of Labour calibration data for Working Level monitors in the RTTF.

Date	Exposure (h)	$\overline{WL}$* (mWL)	Sampler No. 8 (mWL)	No. 89 (mWL)	No. 16 (mWL)	$\overline{MOL}^1$ (mWL)	$\overline{MOL}/\overline{WL}$
July 15-18/85	70.8	203	213	245	238	232	1.14
July 18-19/85	27.1	280	316	317	377	337	1.20
July 24-26/85	47.9	287	323	328	325	325	1.13
						Average:	1.16±0.04

* Average of data obtained with a calibrated continuous Working Level monitor WLM-300 (1 reading/hour), and grab-sampling data (8 samples/day).

[1] Represents the average of the three monitors.

Note: The MOL monitors were operated continuously, i.e., 24 hours/day.

Table 13 - Ministry of Labour calibration data for Working Level monitors MOD-225 in the RTTF.

Date	Exposure (h)	$\overline{WL}$* (mWL)	$\overline{TLD}$(LiF)+ nC	Sampler No. 3080 (mWL)	Sampler No. 3082 (mWL)	$\overline{MOD-225}$[1] (mWL)	$\overline{MOD-225}/\overline{WL}$
July 15-18/85	70.4	203	33.7	200	260	230	1.13
July 24-26/85	47.9	287	27.7	290	240	265	0.92
						Average:	1.03

* Average of data obtained with a calibrated continuous Working Level monitor WLM-300 (1 reading/hour), and grab-sampling data (8 samples/day).

\+ Reading from LiF thermoluminescent detectors (TLD), average of samplers No. 3080 and No. 3082.

[1] Represents the average value of the two monitors.